USASRDL Technical Report 2232

THE EFFECT OF MISMATCHING IN THE MEASUREMENT OF THE AIR-EARTH CURRENT-DENSITY

by

Lothar H. Ruhnke

October 1961

U.S. ARMY SIGNAL RESEARCH AND DEVELOPMENT LABORATORY

FORT MONMOUTH, N. J.

U. S. ARMY SIGNAL RESEARCH AND DEVELOPMENT LABORATORY
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ABSTRACT

The errors are analyzed which arise when using Kasemir's method to measure air-earth current-density. Step function, ramp function, and periodic functions in the current as well as in the time-constant theta of the air are discussed.

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THE EFFECT OF MISMATCHING IN THE MEASUREMENT
OF THE AIR-EARTH CURRENT-DENSITY

INTRODUCTION

Successful measurements of the air-earth current density started in 1906 when Wilson[1] introduced his well-known method which was based on time sampling and was not directly suitable for continuous recording. The difficulty in making a continuous recording was the effect of the potential gradient on the current measurement. In 1933 Scrase[2] tried a method of compensating for this effect, but he did not really succeed although his method is feasible. Adamson[3] rearranged the method of Scrase and used a modern field mill to overcome the sluggishness of the polonium collector used by Scrase. A much simpler circuit for continuous current measurement was introduced in 1955 by Kasemir,[4] who compensated for the displacement current generated by fluctuations of the field in an ingenious way. The errors of this method and the limitations for practical use are discussed in detail in this report.

The three electric parameters most often used to determine atmospheric electric occurrence in fair weather are the field strength F, the sum of the polar conductivities λ, and the conduction current density i. They are combined in the Ohm's law which has, in the three-dimensional case, the form

$$i = \lambda \cdot F. \tag{1}$$

Normally it is sufficient to continuously record two of these quantities in order to determine all three. However, since the measuring instruments, and sometimes the method used, give the measured parameters with a more or less significant error, it should be noted that a measurement of all three variables is necessary to have a continuous check of proper functioning.

One of the most significant errors comes from the influence of the displacement current in air on a conduction-current measurement. This report shows theoretically the expected error when using Kasemir's method of compensation. Starting from the general differential equation, two cases will be treated separately. One is the case when all fluctuations originate from changes in the current density, and the other is the case when all fluctuations come from changes in the conductivities. It is possible to treat these variables separately because the current and the conductivity can be taken in approximation as independent variables.

In discussing the solution of differential equations, it is practical to consider given time functions for the variables. A step function and a ramp function are chosen because they demonstrate the mismatching condition adequately. A step function is chosen because it represents sudden changes in the variables; and a ramp function, which is a function increasing linearily with time, is chosen to represent slow changes. In addition, a frequency-amplitude discussion for periodic fluctuations of the variables is set forth. Frequency-amplitude diagrams in a double logarithmic scale as introduced by Bode[5] are used to interpret the results.

DISCUSSION

Derivation of the Differential Equation

Kasemir's method of current measurement consists of an insulated antenna that is exposed to the atmosphere. This current sensor is grounded by a resistor with a suitable capacitor in parallel. The current through the resistor is measured by a sensitive current meter. The necessary conditions for a true measurement of the conduction current are: the measuring resistor is so small that the voltage drop over it is small compared with the open loop voltage at the antenna, and the time constant T of the RC circuit is at all times equal to the time constant of the air. In practice these conditions are fulfilled in approximation only, even for measurements at the ground. Special difficulties arise when current densities are to be measured as a function of height with balloon soundings because the conductivity of the air is changing exponentially with height. Kasemir,[6] who made the first current measurements with balloons, has made a detailed analysis of the measuring technique involved.

For the antenna, the equivalent circuit diagram as given by Kasemir and Ruhnke[7] is used. It is shown in Fig. 1 where F is the field strength, h the effective height of the antenna, c the antenna capacity, and r the internal resistance of the antenna. The product rc is equal to the time constant Θ of the air surrounding the antenna. The condition that the measuring resistance R should be small is equivalent to the condition that the current measured is the short circuit current in the diagram of Fig. 1. This is normally ful-filled to a satisfactory extent with a measuring resistance of 10^9 ohm because

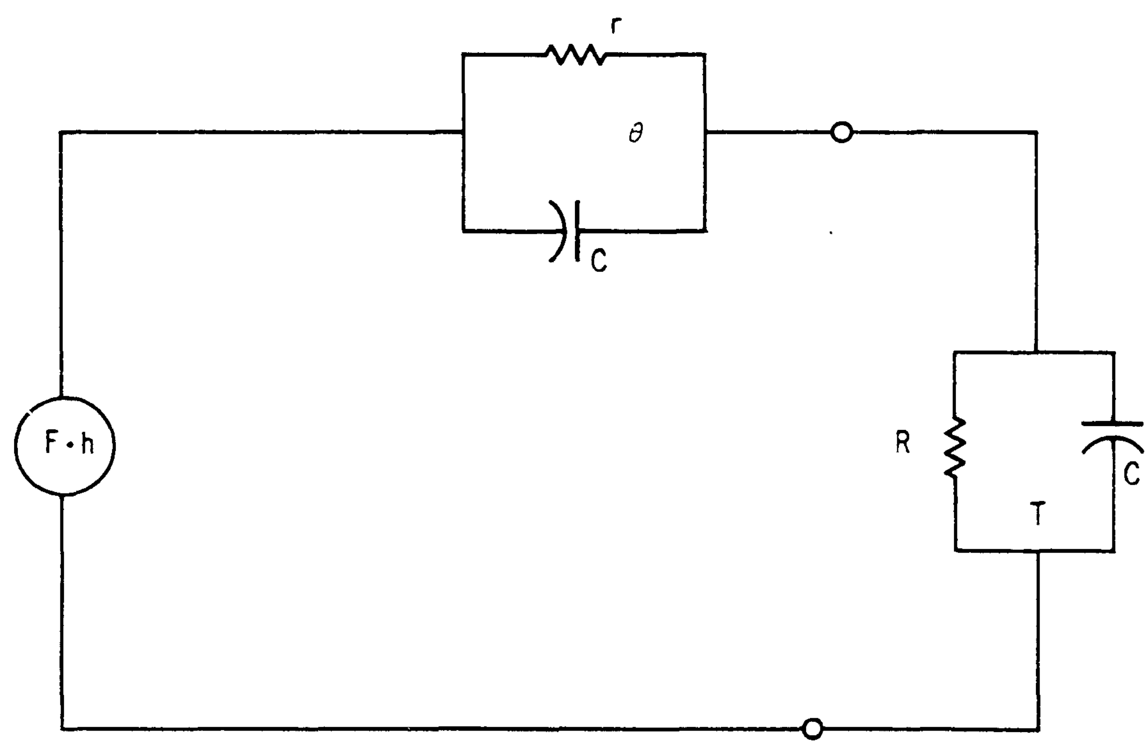

Fig. 1. The equivalent circuit diagram for measuring current density.

the internal resistance r of the current antenna will be in the range of 10^{13} ohms when measured at the gr ind. A more elegant way to satisfy this condition lies in the use of the analog computer technique. An operational amplifier with an electrometer input with the RC network in the feedback loop replaces the current meter and the RC network of Kasemir's method. This arrangement is especially practical if current densities are to be measured in balloon and rocket soundings since, with the exponential increase of conductivity in high altitudes, the short circuit condition is easier fulfilled than with the traditional arrangement. The equivalent circuit diagram for this method is shown in Fig. 2 where the gain A of the operational amplifier for convenience is assumed infinite. Practical values of A are between 60 db and 120 db. It can be shown that the effective input impedance of this circuit at the input of the amplifier is 1/A times the feedback impedance.

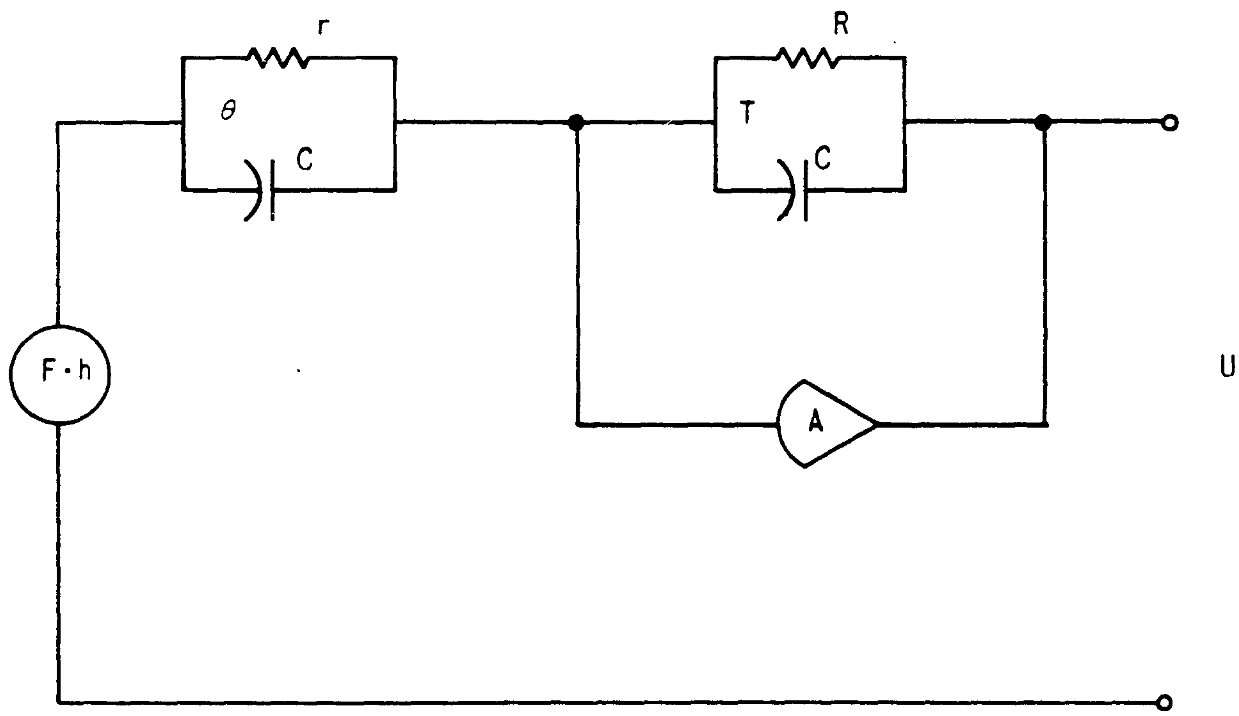

Fig. 2. Circuit with operational amplifier to measure current-density.

One more definition is necessary to set up the general differential equation for this circuit; namely, the desired conduction current density i and a factor M which has the dimension of an area and means the effective area of the antenna. The open-loop voltage Fh is related to the conduction component Mi of the short-circuit current by the internal resistance r.

$$Fh/Mi = r. \qquad (2)$$

The differential equation governing this circuit is then given by

$$U/R + C\, dU/dt = -(Fh/r + c\, dFh/dt). \qquad (3)$$

With equation (2) and with the relation for the time constant, the differential equation can be rearranged.

$$U/R + C\, dU/dt = -(Mi + M\, di\Theta/dt). \tag{4}$$

This equation is valid for homogeneous conductivity and current density in the neighborhood of the antenna. The current as well as the conductivity may, however, be functions of time. The general solution with no initial charges assumed may be expressed by

$$U = -Mir - \frac{MR}{T} \exp(-\frac{t}{T}) \int_0^t \left[i \frac{d\Theta}{dt} + (\Theta - T) \frac{di}{dt} \right] \exp(\frac{t}{T})\, dt. \tag{5}$$

It can be seen that for $\Theta = T =$ constant, the so-called matching condition, U is proportional to the current density i for any time function of i. This is no longer the case if the conductivity changes. Then, $d\Theta/dt$ is no longer zero and this term introduces an r error term into the measurement. But in addition Θ is no longer equal to T, and any current change di/dt brings an additional deviation from the true measurement. The (1) solution of equation (4) for the time functions in question will be obtained by using the Laplace transformation.

The Step Function and the Ramp Function

To demonstrate the influence of mismatching and conductivity fluctuations, a step function for the current i or the time constant Θ, respectively, is assumed. In the first case let Θ = constant and the current jump from the value i to $i + \Delta i$ at t equal zero. The Laplace transformation for this case is given by

$$\frac{U(s)}{R} + sU(s) \quad C - \frac{T}{R} U_{t=0} = -Mi(s) - sM\Theta i(s) + Mi_{t=0}\, \Theta \tag{6}$$

with

$$i(s) = \frac{i + \Delta i}{s};\; i_{t=0} = i;\; U_{t=0} = -MRi.$$

As a matter of convenience let the equation be normalized to a dimensionless one with the help of the relation

$$V = \frac{U}{-MiR}. \tag{7}$$

Now the Laplace equation can be easily solved for V(s):

$$V(s) = \frac{(1 + \frac{\Delta i}{i})}{s} + \frac{\Delta i}{i} \frac{(\Theta - T)}{(1 + sT)}. \tag{8}$$

The time relation V(t) will be obtained after back transformation into the time domain. It contains all transients for the given initial conditions and represents the normalized output.

$$V(t) = 1 + \frac{\Delta i}{i} + \frac{\Delta i}{i} \frac{(\Theta - T)}{T} \exp(-t/T) \qquad t \geqslant 0$$

$$V(t) = 1 \qquad t < 0 \tag{9}$$

This expression means generally that changes of the current which occur fast compared to the time constant T are either exaggerated or damped in the recorded output, depending on the matching condition.

In Fig. 5, relation (9) is plotted against time for three different matching conditions: $\theta = T$; $\theta = 1/2T$; $\theta = 2T$.

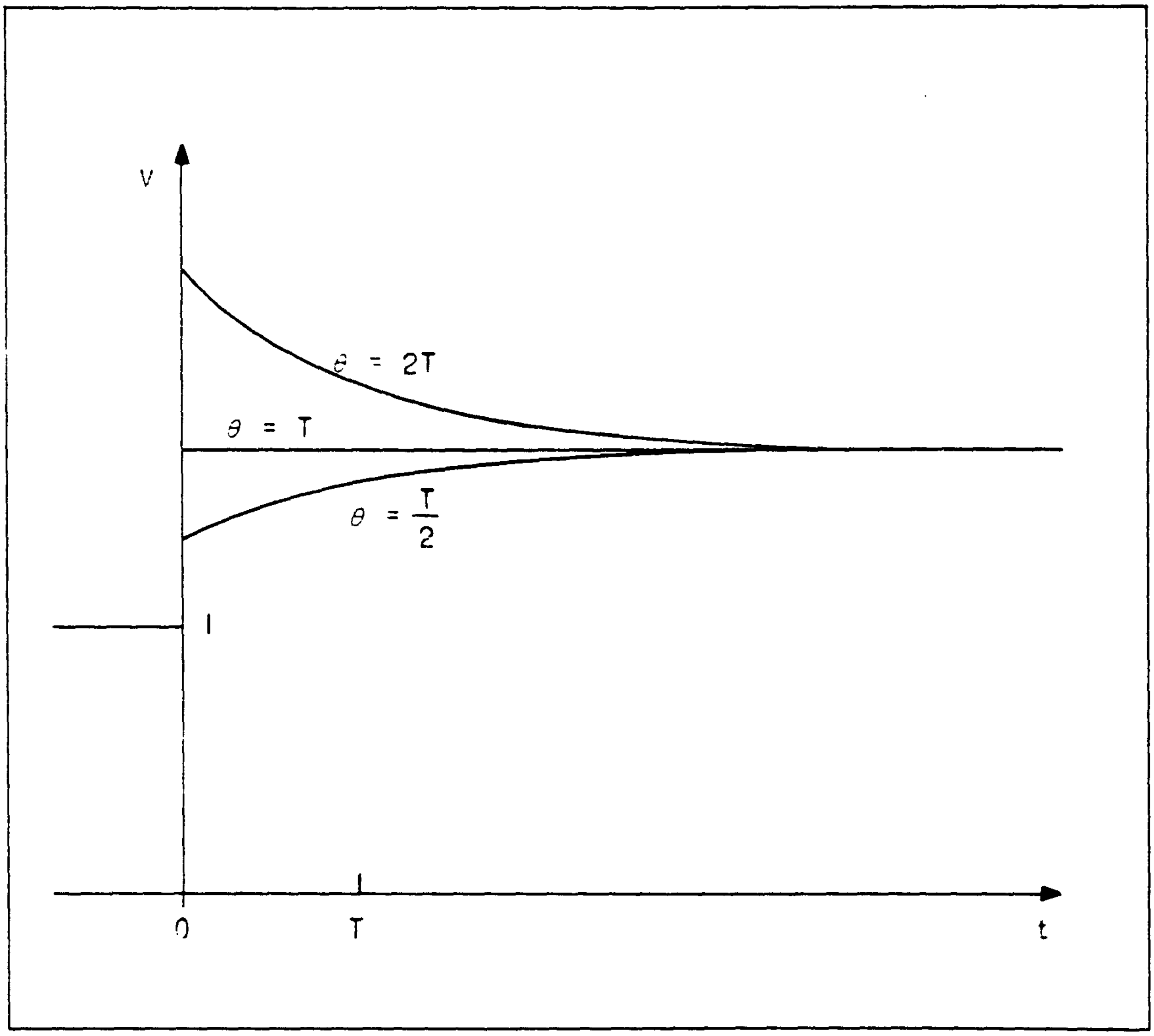

Fig. 5. Circuit response to current-changes for three different matching conditions.

Errors due to changes of the current slow to the time constant T can be treated by assuming a ramp function of the current. Let i (t) be equal to i + Δi/Δt t, with Δi/Δt the rate of current change per time unit. The Laplace transformation then is

$$i(s) = \frac{i}{s} + \frac{1}{s^2}\ \frac{\Delta i}{\Delta t}. \qquad (10)$$

The initial conditions are given by:

$$i(t)_{t=0} = i$$

$$U(t)_{t=0} = -MiR$$

If this is applied to equation (6), and V(s) is solved for,

$$V(s) = \frac{1}{s} + \frac{1}{s^2}\,\frac{\Delta i}{\Delta t i} + \frac{1}{s}\,\frac{(\Theta-T)}{i}\,\frac{\Delta i}{\Delta t} + \frac{T(T-\Theta)}{(1+sT)}\,\frac{\Delta i}{i\Delta t}\,. \tag{11}$$

In the time domain this equation reads:

$$V(t) = 1 + \frac{\Delta i}{\Delta t}\,\frac{t}{i} + \frac{(\Theta-T)}{i}\,\frac{\Delta i}{\Delta t} + \frac{(T-\Theta)}{i}\,\frac{\Delta i}{\Delta t}\exp(-t/T). \tag{12}$$

The first two terms represent the true current component. The term $(\Theta-T)\ \Delta i/\Delta t$ is an error component and means that the current measurement is changed in an amount proportional to $(\Theta-T)$ and to the rate of current change. The last term represents the transient. Summarizing, fast current changes are exaggerated in the reading by the factor $(\Theta-T)/T$ and slow changes bring a constant error of the amount $(\Theta-T)\ \Delta i/\Delta t$.

In Fig. 4 relation (12) is plotted to show the influence of slow current changes. Again the following matching conditions are used: $\Theta = T$, $\Theta = 1/2T$, and $\Theta = 2T$.

In the next case let i be constant and the time constant Θ of the air change at $t = 0$ in a sudden jump from the value Θ to $\Theta + \Delta\Theta$. Equation (5) can then in its normalized form be expressed for this special time function by

$$V = 1 + \Delta\Theta/T \exp(-t/T) \qquad t \geqq 0 \tag{13}$$

$$V = 1 \qquad t < 0$$

Values of T, 1/2T, and 2T are assumed for $\Delta\Theta$ and the output is plotted in Fig. 5.

It is interesting to notice that the error term of equation (13) is no longer zero for $\Theta = T$, but completely independent from the case of matching. The constant part of the time constant Θ does not even appear in equation (13). The magnitude of the error is proportional to the change of Θ and inversely proportional to the time constant T of the measuring device. Changes of Θ, small compared to the time constant T, will not affect the current reading appreciably. In practice the conductivity has strong fluctuations if measured with a Gerdien tube of conventional size. However, the current antenna has an appreciable area and the mean value of the conductivity over this area is responsible for the error term in equation (13). In practice this mean value of the conductivity shows no rapid fluctuations, and the error term is neglectible if current antennas with effective areas over 10 m^2 are used.

For slow changes of Θ, again a ramp function is assumed of the form $\Theta(t) = \Theta + \Delta\Theta/\Delta t\ t$. By using the Laplace transformation, the normalized solution of equation (4) is obtained as

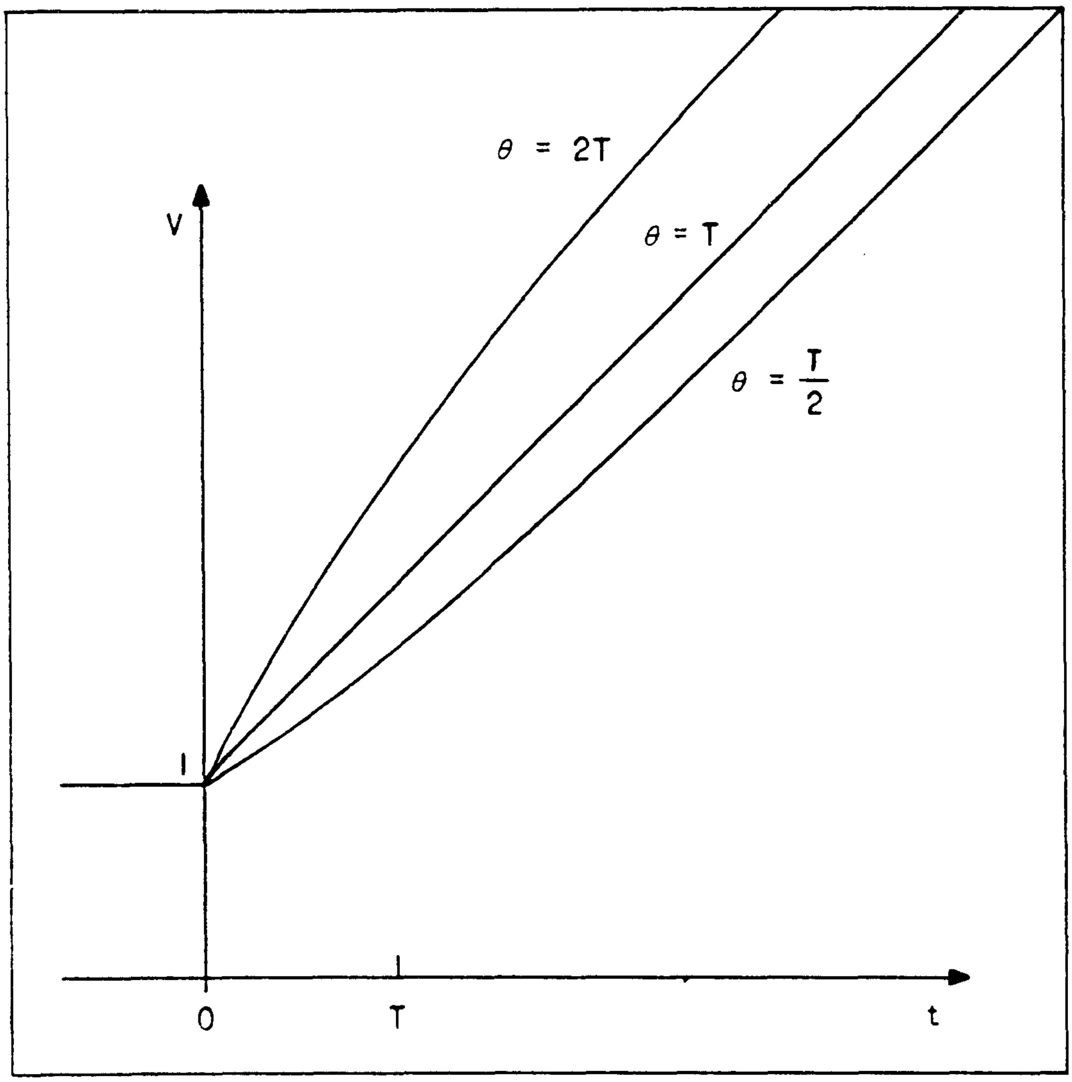

Fig. 4. Circuit response to a ramp function in the current.

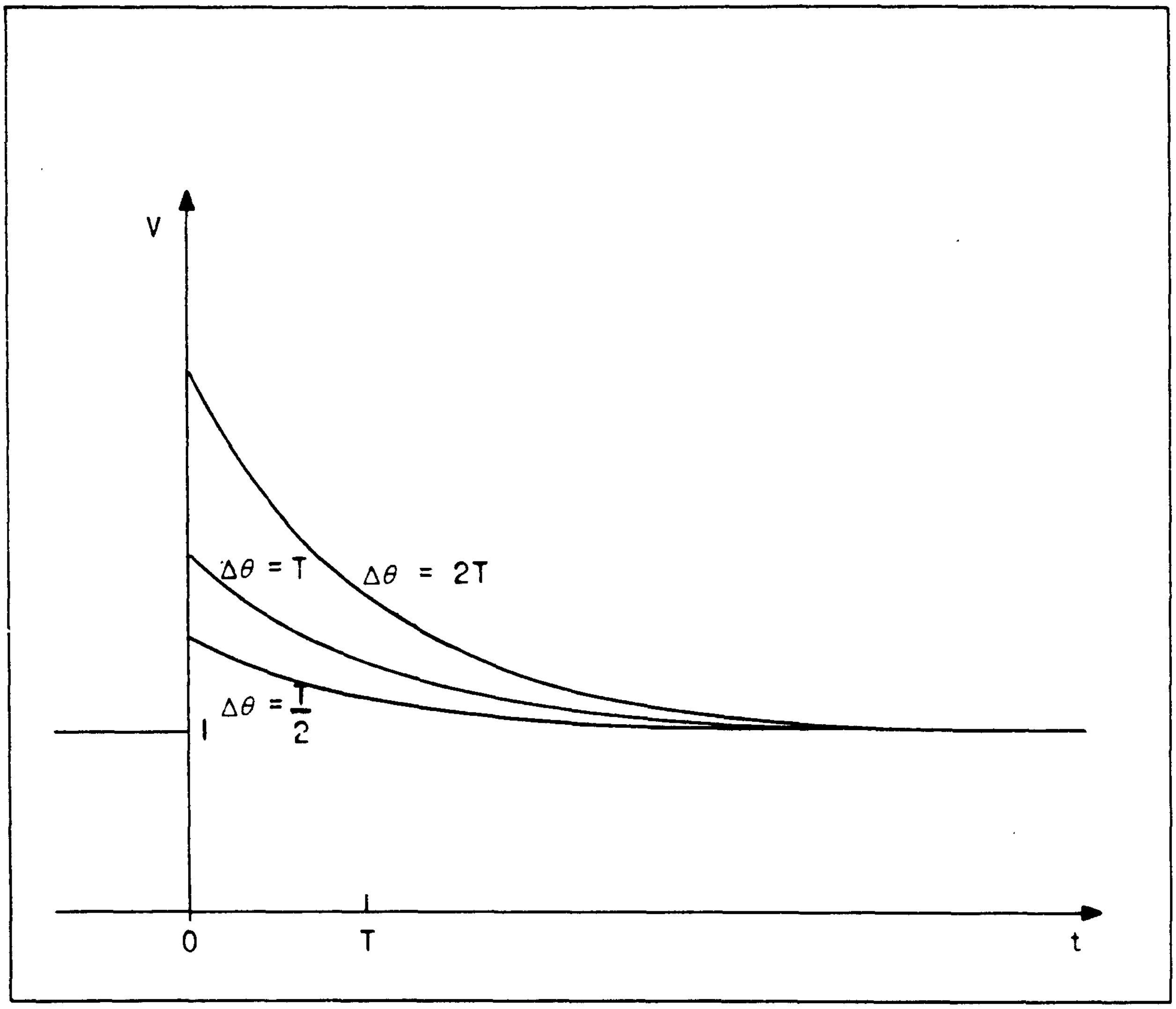

Fig. 5. Circuit response to theta-changes for three different matching conditions.

$$V(t) = 1 + \frac{\Delta\Theta}{\Delta t}(1 - \exp -t/T). \tag{14}$$

Again there is no matching possible, and the error is proportional to the rate of change of the time constant $\Delta\Theta/\Delta t$.

Periodic Functions

The discussion of a step function and a ramp function provides a good demonstration of the effects, but is not sufficient to describe the actual behavior, since random fluctuations may occur in the current as much as in the conductivities with no similarities to step or ramp functions. A more precise description of the phenomena involved is given by a complex frequency characteristic of the system. There are often quasi periodic fluctuations observed in the recordings of atmospheric electric parameters, and with the known frequency characteristic of the system it is easy to estimate the existing error for a specific frequency. The sine wave is probably of all time functions the one which best approximates the measured fluctuations. Besides this, it is possible to present any time function by its spectrum obtained by Fourier analysis. The spectrum of the output is then equal to the spectrum of the input times the frequency characteristic $V(j\omega)$ of the system. The error term of the system is given by the deviation of the transfer characteristic from unity. In other words, a correct current measurement is obtained if $V(j\omega)$ is equal to unity for all frequencies.

To obtain the transfer function of the system, assume periodic functions of i and Θ and consider the solution of equation (4) after decay of the transients. To do so, make use of solving differential equations with the help of the Laplace transformation. The transformed equation itself acquires for periodic functions of i the significance of a frequency characteristic when the complex variable s is substituted for by the cyclic frequency $j\omega$. However, the transfer characteristic is not obtained so easily when periodic functions of Θ are assumed and the current remains constant. It is therefore preferable to derive the transfer function in the exact manner. The Laplace transformation of equation (4) for the case Θ = constant, then, is

$$U(s)(1+sT) - TU_{t=0} = -MRi(s) - MR\Theta si(s) + MR\Theta i_{t=0} . \tag{15}$$

The initial conditions are $U_{t=0}$ and $i_{t=0} = 0$. The current as a periodic function may be expressed as

$$i(t) = i \exp(j\omega t) \tag{16}$$

and its transformation as

$$i(s) = i/(s - j\omega). \tag{17}$$

The transformed differential equation then has the appearance:

$$U(s) = -MRi\ (1 + s\Theta)/(1 + sT)\ (s - j\omega). \tag{18}$$

By using the standardizing relation (7), and after decay of the transients, the time relation after inverse transformation is obtained.

$$V = (1 + j\omega\Theta)/(1 + j\omega T) \exp(j\omega t). \tag{19}$$

This equation can now be discussed. $\Theta = T$ is the matched condition and for this $|V| = 1$. For any other value of the time constants there is a frequency dependence of V. In Fig. 6 the absolute value of V is plotted against the inverse frequency (cycle length) in a double logarithmic scale. The amplitude is expressed in decibels and the circuit is matched when the conductivity has a value of 10^{-14} $ohm^{-1}m^{-1}$.

For cycle lengths long compared to $2\pi T$ or $2\pi\Theta$, $|V|$ is unity and no errors exist. For cycle lengths short compared to $2\pi T$ or $2\pi\Theta$, $|V|$ is constant and has the value Θ/T. For cycle lengths between $2\pi T$ and $2\pi\Theta$ there is a smooth transition from unity to Θ/T.

For the case that i is constant and Θ is the variable, the transformation of equation (4) is obtained:

$$U/R\ (1 + sT) - T/R.U_{t=0} = -Mi/s - sMi\ \Theta\ (s) + Mi\Theta_{t=0}. \tag{20}$$

with $U_{t=0} = -MiR$, $\Theta\ (s) = \Theta/(s - j\omega)$.

Again normalize this equation and neglect the transients. Transforming this equation back into the time domain,

$$V = 1 + j\omega\Theta/(1 + j\omega T) \exp(j\omega t). \tag{21}$$

The absolute value of the error term is plotted in Fig. 7. For periodic changes of Θ which have a cycle length long compared to $2\pi\Theta$, $|V|$ approaches unity and there is no influence of conductivity changes on current measurements. For a cycle length short compared to $2\pi T$, an error term of the absolute value Θ/T and with the cyclic frequency ω is obtained. This error term is superimposed on the constant current.

How much conductivity changes affect the current recording in practical cases cannot be stated definitively without knowing the average spectrum of the conductivity fluctuations. However, examination of simultaneous current and conductivity recordings does not show any clear transfer of conductivity fluctuations on the current reading. This is an indication that the spectrum of the conductivity has no significant component in the cycle length region short compared to $2\pi\Theta$.

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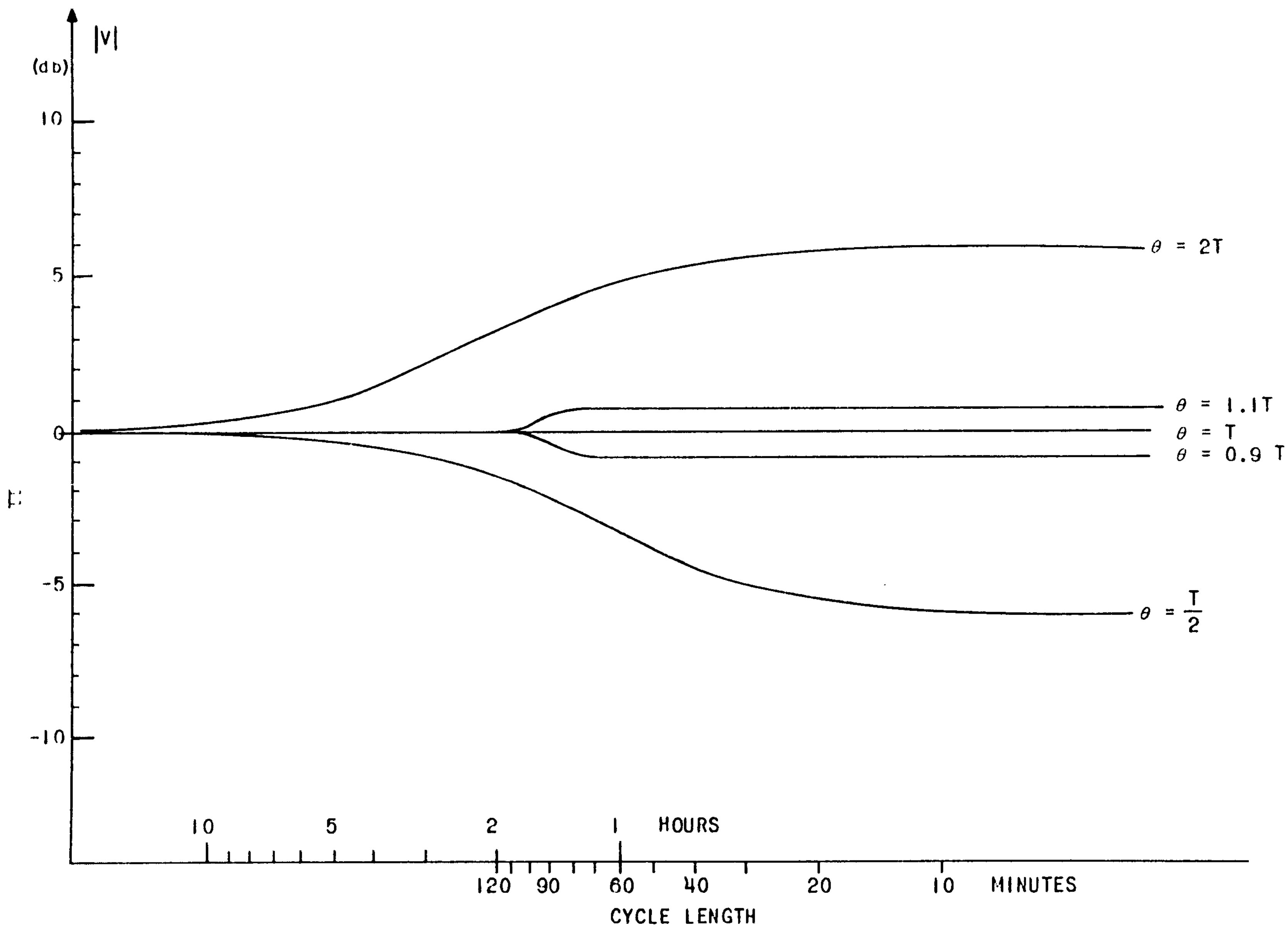

Fig. 6. Circuit response to periodic current changes.

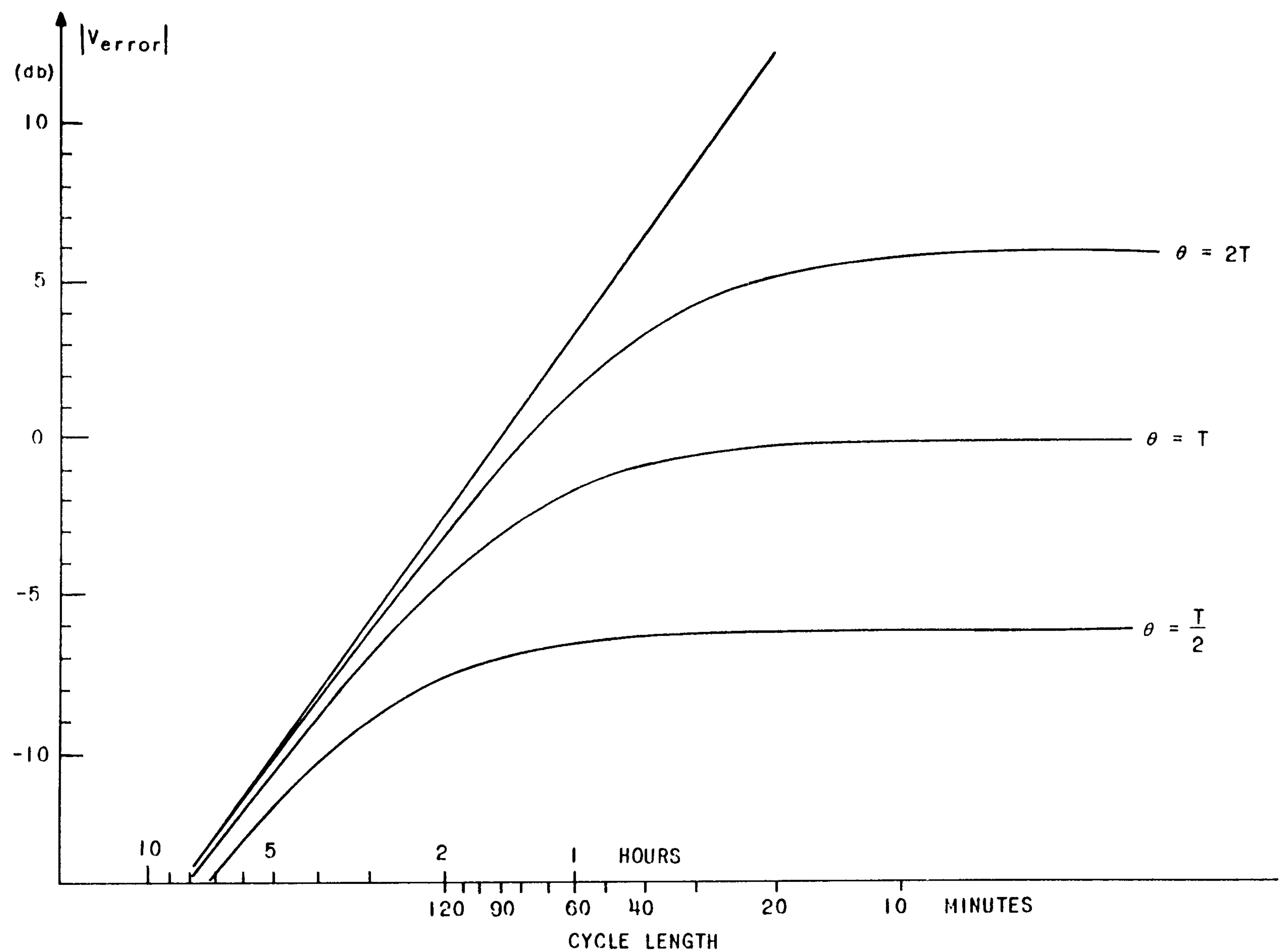

Fig. 7. Error in the current-measurement due to periodic changes in the time constant.

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THE EFFECT OF MISMATCHING IN THE MEASUREMENT OF THE AIR-EARTH CURRENT-DENSITY by Lothar H. Ruhnke. October 1961, 13 pp incl. illus, 7 ref. (USASRDL Technical Report 2232) (DA Task 3A99-27-005-03) (Unclassified Report)

The errors are analyzed which arise when using Kasemir's method to measure air-earth current-density. Step function, ramp function, and periodic functions in the current as well as in the time-constant theta of the air are discussed.

1. Step function
2. Ramp function
3. Periodic functions

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